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Orbits of Saturn's Inner Moons and Other Observations Connected with the 1995-1996 Saturnian Ring Plane Crossing
NAGW-4659 5/95-9/97

FINAL REPORT

1) Keck Telescope

We obtained images of Saturn's rings (and also a small number of images of the rings of Uranus and Neptune before Saturn rose) on the Keck telescope for 3 half-nights surrounding Earth's first crossing of Saturn's ring plane, 1995 May 20-22. Full nights of data were taken surrounding Earth's second ring plane crossing, 1995 August 9-11. We attempted to take data following the Sun's ring plane crossing in 1995 November, but were unsuccessful as a result of weather and telescope problems. We have reduced all of our Saturn data taken in May and a small fraction of (the much larger amount of) the August data. The data reduction is very time consuming, as essentially every frame (one frame per 30 seconds, on average) has to be dealt with individually.

We have reported (de Pater et al. 1996) the first clear detection of the E and G rings in K band; this was also the first detection of the G ring from Earth at any wavelength. The E ring's radial and vertical structure was found to be generally consistent with previous results from Voyager and Earth-based observatories; it has a brightness peak near the orbit of Enceladus and extends outward to ~ 6 Saturn radii. The E ring is ~ 40% fainter at K band than in the visual, confirming and extending previous reports that it is very blue in color. The G ring's reflected intensity is similar to that found in the comparable Voyager image, implying that this ring is neutral in color form the visual to the infrared.

2) IRTF

We obtained data on three nights at each of Earth's first two ring plane crossings, 1995 May 20, 21, 24 and 1995 August 6-8. The IRTF data have been completely reduced and analyzed. The results of this analysis have been published (Bauer et al. 1997) and are presented in more detail in Bauer's (1996) Masters' Thesis. We derived brightness values at K band for both the E and G rings and our results are consistent with those obtained at Keck. We detected the E ring in H and J bands as well as in K; the peak effective thickness (the product of the thickness, optical depth and albedo) of the E ring at J is about 65 meters, at H is about 40 meters and is slightly less than 40 meters at K; these results show how the blue color of the E ring extends to the near-IR. We also reported infrared magnitudes of the moons Hyperion, Mimas, Janus, Epimetheus and Helene, as well as the timing of a passage of Enceladus into Saturn's shadow. Our IRTF data has been sent to the Planetary Rings Node of the PDS for archiving. It has also been sent to a group of researchers from ESO who are trying to extend the baseline of their observations for arcs in the F ring.

3) Palomar

Immediately following the solar crossing of Saturn's ring plane on 1995 November 19, three nights were devoted to observing the rings and satellites with the 5-m Hale Telescope at Palomar Observatory. The observations were carried out by P. Nicholson (Cornell) and colleagues, with travel support for PDN provided by the

present grant. Observing conditions were generally excellent, and a large number of near-IR images of the rings were obtained under conditions of almost edge-on illumination, using a special purpose 2.3 micron methane filter to suppress scattered light from Saturn. These data should contribute to studies of the photometric properties of the rings, but have yet to be analyzed in any detail. The primary emphasis of the observations, however, was on monitoring occultations and eclipses of the moons of Saturn, with a particular goal of observing events involving the small, inner satellites in order to improve their orbits.

These observations were quite successful, and preliminary results were presented at the Tucson DPS meeting in October 1996 (Nicholson et al. 1996b), and at the Workshop on Satellite Mutual Events held in Catania, Sicily in March 1997. In all, eleven eclipses and occultations were observed, including three by Janus (the larger coorbital satellite) and one by its smaller coorbiting companion, Epimetheus. These are the first such observations ever made for the inner satellites, and indicate longitude errors of about ~ 0.35 deg in the pre-1995 ephemeris of Janus and ~ 0.6 deg for Epimetheus. These are comparable to results obtained from astrometry of HST images (Nicholson et al. 1996a).

4) Radio Observations

Floris van der Tak, in collaboration with Imke de Pater, Adriana Silva and Robyn Millan (all UC Berkeley), imaged Saturn at radio wavelengths, a project which was (in part) funded under this grant. Such data contain information on the structure and composition of the rings as well as the planet's deep atmosphere between the 1- and 10-bar pressure levels. We have recently reduced and partially analyzed several data sets taken prior to and during the ring plane crossing in 1995. These radio images show Saturn's Southern hemisphere for the first time. All data were obtained with the Very Large Array of the National Radio Astronomy Observatory (VLA), except the 0.3 cm data which were taken with the Berkeley-Illinois-Maryland Association (BIMA) array. In addition, we obtained an upper limit of 600 K (2 sigma) on the planet's total brightness temperature at 90 cm from VLA data taken in 1992.

Our 2 cm 1994 data are completely unlike the planet's appearance in previous years, which at 2 cm used to be featureless to within 1%. In contrast, in 1994 the planet displays two bands in the Northern hemisphere at 2 cm. This marks a clear deviation from long-term equilibrium in the atmosphere, as has been widely assumed until now. In addition, in our 6 cm VLA data from 1995, the band that had been present throughout the '80s had disappeared, and was 'replaced' by a bright band in the Southern hemisphere. The complementary BIMA 0.3 cm data, taken quasi-simultaneously, show no deviations from an even brightness structure.

The images were compared with atmospheric models similar to those described by de Pater & Mitchell (1993). These models allow the concentration of the main trace constituents to vary with altitude. At high pressures, the concentration of gaseous ammonia, the main source of opacity in the microwave regime, is enhanced by a factor 3 with respect to solar. At pressures below about 6 bar, however, most ammonia condenses out in the form of ammonium hydrosulfide, causing a decrease in gaseous ammonia abundance below 4 bar. Earlier work demonstrated that this condensation effect is essential in producing the observed broad-band radio spectrum of Saturn and

Jupiter (e.g., de Pater and Massie 1985; Briggs and Sackett 1989; de Pater and Dickel 1991).

Modeling the observed bands requires a latitude-dependent atmospheric model. There are two ways to explain changes in Saturn's 6 cm brightness. Either the humidity in the ammonium hydrosulfide cloud departs from its equilibrium value of 100%, or the base of this cloud is at lower pressure levels (e.g., de Pater and Dickel 1991). The flat brightness profile observed at 3.6 cm sets a strict lower limit of 85% to the cloud humidity in the band. Due to the superb image quality, the combined 6 and 3.6 cm data allow only a very small range of humidities and cloud base levels. Similar considerations hold for our 1995 data, although the range of atmospheric models for the Southern bright band is somewhat larger due to the lower angular resolution of the BIMA telescope. The bands seen at 2 cm in 1994 arise at a significantly lower pressure level than the 6 cm bands, and can be fully explained by humidity effects. Unfortunately, we do not have simultaneous 6 cm data from that period, which would have helped to constrain atmospheric models.

The 1990 and 1994 images also show superb pictures of Saturn's rings, in absorption across the planet, and in emission on either side of it. At least in 1990, the radio emission has significant linear polarization, in a direction changing gradually across the rings' surface. Both data sets confirm the E-W asymmetry of the rings where, like in earlier images (de Pater and Dickel 1991) the West side is always brighter than the East side of the rings.

Publications & Theses supported by this grant

1. de Pater, I., M.R. Showalter, J.J. Lissauer and J.R. Graham, 1996. "Keck Infrared Observations of Saturn's E and G Rings during Earth's 1995 Ring Plane Crossing" *Icarus*, **121**, 195-198.

2. Bauer, J. M.1996. "IRTF Observations of Saturn's Faint Outer Rings and Small Moons in the Near-IR" Astronomy Program, State University of New York @ Stony Brook.

3. Bauer, J.M., J.J. Lissauer and M. Simon, 1997. "Edge-On Observations of Saturn's E and G Rings in the Near-IR" *Icarus*, **125**, 440-445.

Abstract published:

Bauer, J., J.J. Lissauer and M. Simon, 1996. "IRTF Observation of Saturn-Earth Fing Plane Crossing: Faint Outer Ring Near-IR Profiles" *Lunar & Planetary Science Conference XXVII Abstracts Book* 79.

Oral Presentations:

Jack J. Lissauer

"Les Anneaux de Saturne" L'Institut d'Astrophysique, Paris, FRANCE, Oct. 8, 1996 (in French).

James Bauer

"IRTF Observation of Saturn-Earth Fing Plane Crossing: Faint Outer Ring Near-IR Profiles" Lunar and Planetary Science Conference, Houston, TX, March 1996.

"IRTF Observations of Saturn's Faint Outer Rings and Small Moons in the Near-IR" State University of New York, Stony Brook, NY, June 1996.

Additional References

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de Pater, I. and J.R. Dickel 1991. *Icarus* **94**, 474.
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